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CONFIGURATION OF OPTIMAL CROSS BORE SHAPE IN ELASTIC PRESSURIZED HIGH PRESSURE VESSELS

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ABSTRACT

Numerous analyses were performed to establish the optimal shape between circular and elliptical plain cross bore at both radial and offset positions in closed thick walled cylinders. Seven cross bored cylinders with thickness ratios between 1.4 and 3.0 were studied. For effective comparison between circular and elliptical cross bores, the major radius of the elliptical cross bore was equal to that of circular cross bore. The behaviour of hoop stresses together with that of Stress Concentration Factors (SCF) were investigated at offset location ratios ranging from 0 to 0.9 using a three dimensional linear finite element analysis. Elliptical shaped cross bore predicted lower hoop stresses at radial position than circular ones, with a variation of 44.6% to 66.9% across the studied thickness ratios. With exception of K= 2.25, circular cross bores predicted lower hoops tress at 0.9 offset location ratio than elliptical ones. The minimum SCF magnitude due to circular cross bore occurred at 0.9 offset position in K=1.4, with a magnitude of 2.312. On the other hand, the lowest SCF magnitude produced by elliptical cross bore occurred at radial position with magnitude of 1.733 at thickness ratio of 2.5. This magnitude predicted by the elliptical cross bore also doubled as the overall optimum SCF in this study. For a circular cross bore, coincidence in SCF between the optimum thickness and location occurred in K=1.4 at the 0.9 offset position which also gave the best circular shape. Whereas for an elliptical shape, similar coincidence in SCF occurred respectively in K=1.75 and 2.5 at 0.685 and 0 offset positions. In conclusion, optimal location of elliptical cross bores reduce SCF magnitudes by 33% in comparison to a similar circular cross bore. However, an incorrect positioning of the same cross bore may lead to a rise of SCF magnitude by 121%.

***KEYWORDS:** Pressure Vessels, Cross Bore Shape, Cross Bore Location, Thickness Ratio, Hoop Stress & Stress Concentration Factor*

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Original Article

1. INTRODUCTION

Stress concentration is one of the most important parameters to be considered in the design of pressure vessels. It is associated with persistent difficulties encountered during the design and operation of pressure vessels such as fractures, fatigue failures and local yielding [1, 2]. A combination of these difficulties often result to failures of pressure vessels. Failure of pressure vessels is usually catastrophic leading to loss of life, property and in some instances cause severe environmental pollution [3].

Stress concentration is caused by various kinds of discontinuities. These discontinuities act as stress raisers altering the uniform stress distribution around their vicinity [4]. The main forms of discontinuities include geometric, metallurgical and load [1, 3]. Though, the former has been proven to have more adverse effects on stress concentration than the others. Examples of geometric discontinuity which are caused by rapid

change in shape of the component include holes, cavities, notches, fillets, grooves and definable cracks [2, 4]. Stress concentrations arising from this type of discontinuity are measured using a dimensionless factor called Stress Concentration Factor (SCF) [5, 6].

Pressure vessels are constructed with holes or openings on their walls to provide provision for fitting essential operation and maintenance accessories such as fluid transfer, instrumentation, bursting caps, among others [4]. These openings on pressure vessel walls are known as cross bores or cross holes. Despite their importance in the design of pressure vessels, cross bores act as forms of stress raisers.

The magnitude of stress concentration arising from the introduction of cross bore depends on its configuration geometry. The major parameters of the cross bore configuration geometry being the size, location, obliquity angle, thickness ratio and shape [7]. Positioning of cross bores in highly stressed elements result to severe weakening of the vessel especially when there is frequent fluctuation in state of stress [1]. Even though fluctuation in the state of stress is a common phenomenon experienced during the use of the pressure vessels [7].

Since fatigue failures and cracks initiate from regions of high stress concentration, there is need to optimise these geometric parameters with a view to establish the minimum stress concentration. Some of the benefits derived from optimization of the cross bore geometry include low safety factors, high working pressures, economic use of materials, high efficiencies, provision of high safety standards, improved availability and reliability of equipment [4, 6].

Various types of cross bore shapes such as circular, elliptical, rectangular and notches are used in the design of pressure vessels for different applications [7]. Though, only circular and elliptical shapes are commonly used [4]. Construction of cross bores in the wall of the cylinder generate high stress magnitudes especially at the intersection of the cross bore and the main bore. To counteract these high stresses, design features such as chamfers, blends and radii are introduced in an otherwise plain cross bore. Numerous authors [2, 4, 8, 9] have studied the effects of the cross bore features on stress concentration. A summary of their findings are detailed in a review study by Nziu and Masu [7]. However, optimization studies on the shape of the cross bore particularly at the offset positions are not exhaustive.

Therefore, this study seeks to establish the optimal shape between circular and elliptical plain cross bore at both radial and offset positions for various closed thick walled cylinders.

2. METHODOLOGY

2.1 Selection of the Geometry

Closed thick cylinders with thickness ratios of 1.4, 1.5, 1.75, 2.0, 2.25, 2.5 and 3.0 were investigated. Throughout this study, the main bore diameter was kept constant at 0.05 m. For effective comparison between the elliptical and circular cross bores, the major radius of the elliptical cross bore, denoted as "a" was equal to that of the circular cross bore. Because the stress generated due to the introduction of the cross bore is affected greatly by the orientation of the major diameter. Similarly, the major radii of the two cross bores shapes were kept constant at 0.0025 m.

Optimal elliptical cross bore with diameter ratio of 2 was positioned such that the minor diameter of the cross bore was parallel with the axial direction of the cylinder. This cross bore arrangement had been proven to give lowest stress concentration, as suggested by Makulsawatudom *et al.,* [4] and Faupel and Fisher [10] studies.

A configuration showing the arrangement of these two cross bores is shown in Figure 1.

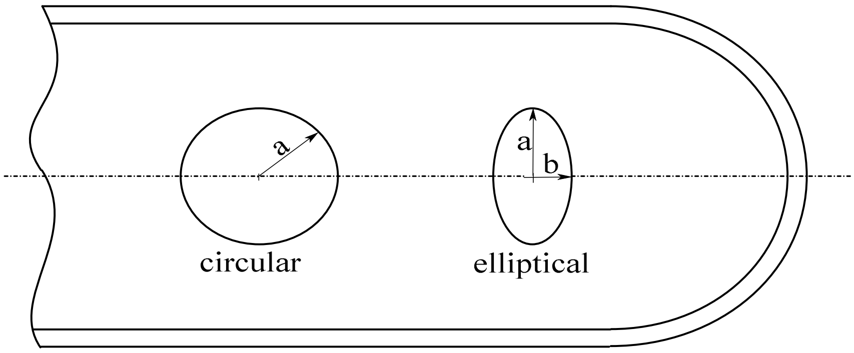

Figure 1: Cross Bore Configuration.

where

- a is the radius/ major radius
- b is the Minor radius

2.2 Location of the Cross Bore

In all the cylinders studied, the two shapes of cross bores were positioned at five different locations along the radial X-axis of the vessel, as illustrated in Figure 2.

The offset distance was measured from the central axis of the main cylinder to the transverse axis of the cross bore. However, for the effective comparison of these results, the offset distances were converted to offset location ratio by dividing the actual offset distance $\bar{x}$, with the main bore radius R_i, i. e., ${}^{\bar{x}}/_{R_i}$. The five offset location ratios which were studied include 0, 0.24, 0.48, 0.685 and 0.9. The chosen offset ratios of 0.24 and 0.9 were relatively similar to those studied in the technical literature by Masu [6] and Cole *et al.* [11] and for easier validation of the finite element modelling.

where

- $\bar{x}$ is the actual offset distance
- R_i is the main bore radius
- θ is the included angle

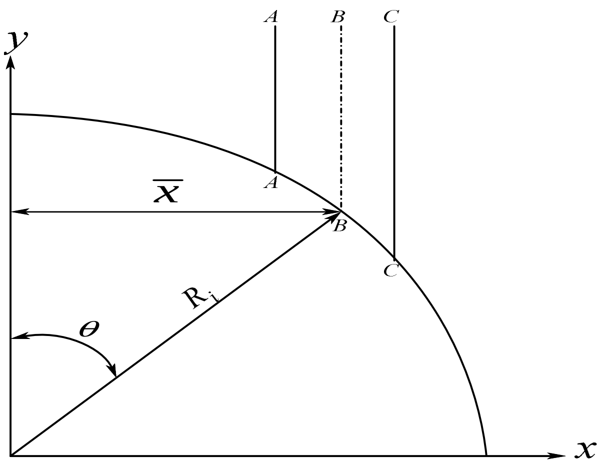

Figure 2: Cross Bore Location.

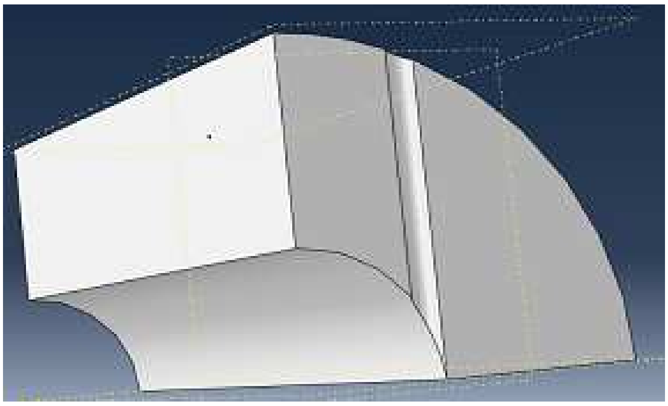

Figure 3: Part Profile of a Selected Model.

2.3 Finite Element Analysis

Three dimensional linear finite element analysis was performed using a commercial engineering software called Abaqus version 6.16. The choice of this particular software was based on its availability and capability to model axis-symmetrical structures. For this work, a total of 70 different models were constructed and analysed. Due to symmetrical nature of the cylinder, only an eighth profile of the structure was used. This technique of using a fraction of the model reduces both the computer memory and its processing time.

The standard procedures followed in Abaqus modelling software are presented under the following subheadings:

2.4 Creation of a Model

A three dimensional deformable solid body was constructed as shown in Figure 3.

The length of the cylinder was made three times the external diameter to ensure that the effects of the close ends are not transmitted to the other far end.

2.5 Creation of Material Definition

The entire modelling process was performed under linear elastic conditions. The following material properties were used; Young modulus of elasticity 190 GPa, Poisson’s ratio 0.3 and density 7800 $\mathrm{Kg/m^3}$. The material properties used in this simulation were similar to those reported in the reviewed literature by Chaudhry *et al.*,[12] and Choudhury *et al.*,[13].

2.6 Assigning of Section Properties and Model Assembly

The properties of the whole model profile were described as solid and homogenous. This task enabled the creation of a single assembly which was independent of the mesh. The entire model, indicated in Figure 3, was then oriented to conform to the global Cartesian co-ordinates axes i. e. X, Y and Z axes.

2.7 Analysis Configuration

The configuration of this simulation analysis was done by creation of a static pressure step. It is worthy to note that the application of different types of loads and boundary conditions are interlinked to each step of the analysis. This action was followed by the creation of a set out point which defines the history output. The set out point was positioned at the intersection of the main bore and the cross bore. Thereafter stress was selected as the required field output request.

2.8 Application of Boundary Conditions

To prevent any rotation and rigid movement of the model, symmetry conditions were applied at the cut section of the model. The symmetry conditions were applied at cut regions in X, Y and Z axes. The careful application of these boundary conditions ensured that no errors occurred due to the Poisson's effect. According to Adams and Askenazi [14] the Poisson's effect occurs due to incorrect positioning of boundary conditions. The incorrect boundary conditions restrict the material deformation causing a couple strain, hence the occurrence of the Poisson's effect. Note that, the Poisson's effect error is given as 5% [14].

2.9 Application of loads

The model was then loaded with an internal pressure of 1MPa at both the main bore and the cross bore in accordance with the standard practice in the analyses of pressure vessel. In addition, a uniform axial stress calculated using lame's equation was applied at the far end of each cylinder to simulate the end effects generated by the closed end closures in the pressure vessels. The magnitude of axial stresses calculated are shown in Table 1.

2.10 Meshing of the Model

The refinement of the mesh was done using a combination of H and P-element techniques. The H-element refinement technique was achieved by dividing the model into small geometrical sections. Further, the mesh around the vicinity of the cross bore was biased by increasing the number of elements. This process of increasing the number of mesh elements is referred to as mesh density. High mesh density increases the capture of the localised stresses leading to high levels of accuracy without significantly increasing the computer run time. On the other hand, the P-refinement technique which depends on the degree of polynomial was obtained using second order differential equations by reduced integration method.

The accuracy of the finite element analysis results depends on the quality of the mesh elements and their density. The mesh verification was done to establish the element quality and identify any distorted elements. The degree of element distortion depends on the capability of the software and its tolerances, element shape and size, among other factors. Generally, element distortion leads to erroneous results. Thus, to eliminate the occurrence of element distortion, the percentage tolerance for both the element warnings and errors were kept at zero. In fact, the elements were found to converge whenever their sizes were between 0.003 and 0.004 m

The shape of the element was made in accordance with Abaqus 6.16 documentation guidelines. According to this guidelines, only second order hexahedral and tetrahedral elements are recommended for stress concentration problems. Hexahedral elements usually give results with a high degree of accuracy [15] compared to other alternative elements. Whereas, tetrahedral elements are less vulnerable to distortion because they are less sensitive to their initial shape.

Thus, 20-noded second order, C3D20R hexahedral (brick) isoperimetric elements were used for modelling in all radial cross bores. Whereas, second order C3D10 tetrahedral elements with 10 nodes were used in all offset positions. A meshed profile of the model part is shown in Figure 4.

Table 1: Axial Stresses

K	1.4	1.5	1.75	2.0	2.25	2.5	3.0
σ_z (MN/m^2)	1.04166	0.80	0.485	0.333	0.246	0.190	0.111

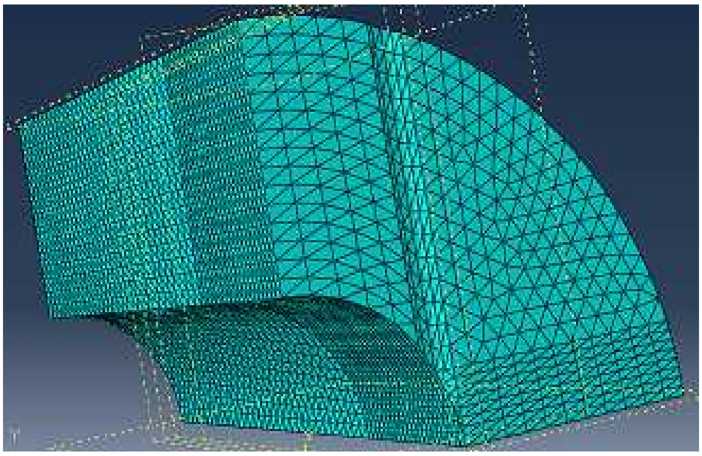

Figure 4: Selected Profile of the Mesh.

2.11 Validation of the Model

Theoretical models obtained using Lame's theory were used to validate results obtained from the FEA models. Validation of the results was done by comparing the FEA displacements and principal stresses (hoop, radial and axial), with their corresponding theoretical results in areas far away from the cross bore [2, 8]. The effects of any form of geometric discontinuity is limited to the regions surrounding it. In case of a cross bore, the effects are approximated to be a linear length of 2.5 cross bore diameter [2]. Further, validation of the model was done using results from other similar related works in the reviewed literature.

3. RESULTS AND DISCUSSIONS

The comparison between stress profiles given by circular and optimum elliptically shaped cross bores at each offset position are discussed under the following sub headings;

3.1 Effects of Cross Bore Shapes on Maximum Principal Stresses

Figures 5 to 11 show the comparison of maximum principal stresses predicted by circular and elliptical cross bores together with a plain cylinder at each offset position for thickness ratios K=1.4, 1.5, 1.75, 2.0, 2.25, 2.5 and 3.0.

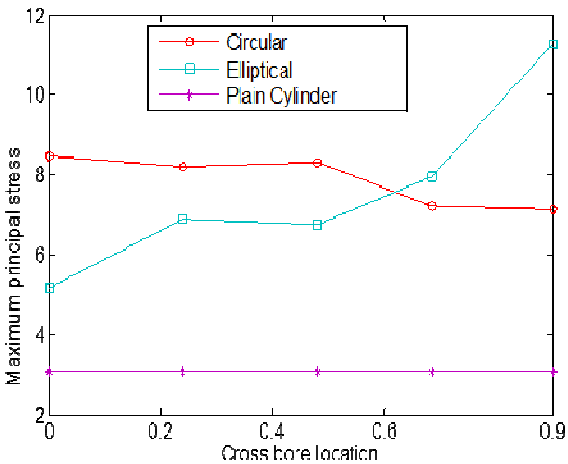

Figure 5: Offset Cross Bore for K=1.4.

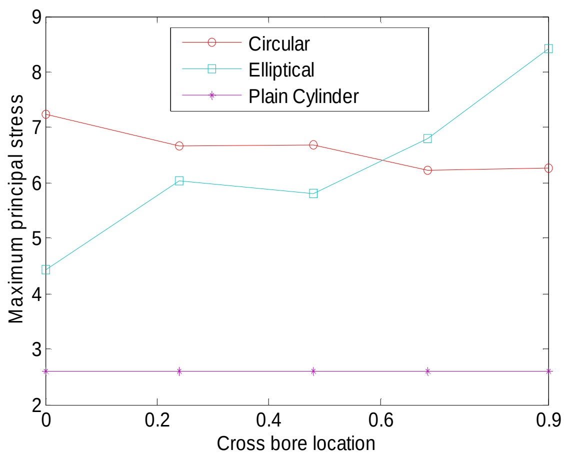

Figure 6: Offset Cross Bore for K=1.5.

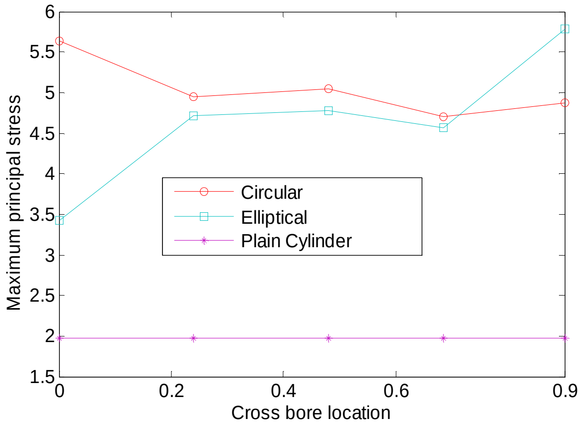

Figure 7: Offset Cross Bore for K=1.75.

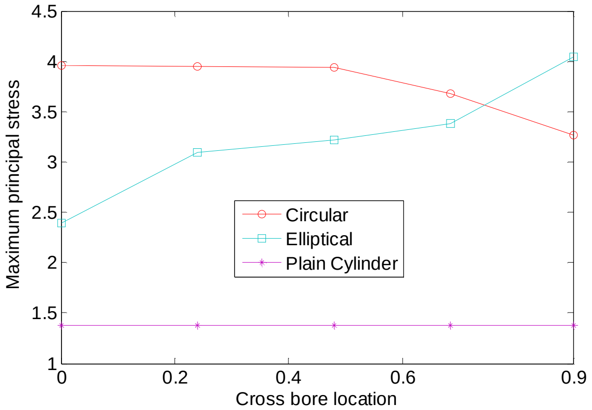

Figure 8: Offset Cross Bore for K=2.0.

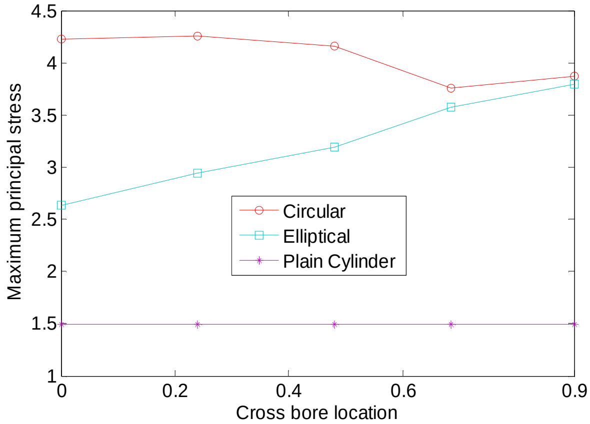

Figure 9: Offset Cross Bore for K=2.25.

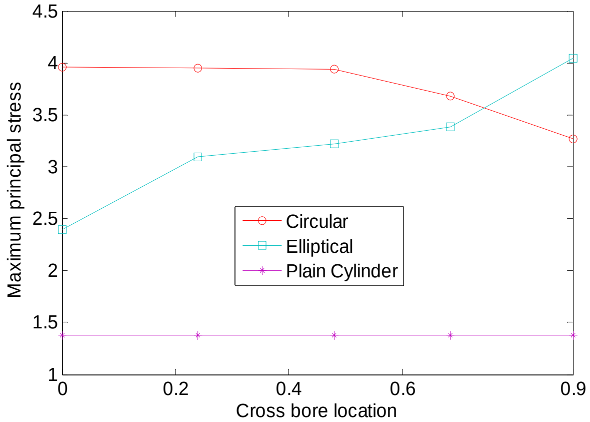

Figure 10: Offset Cross Bore for K =2.5.

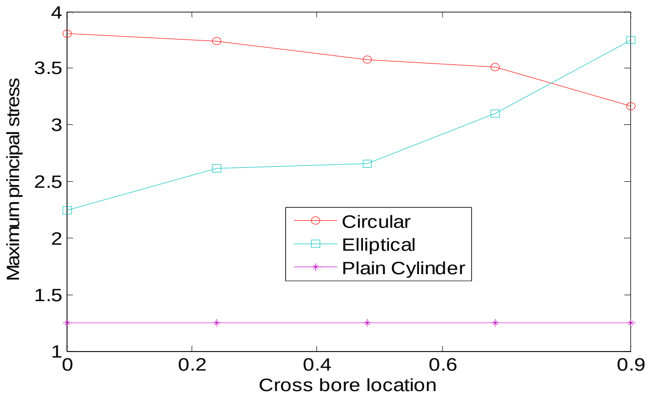

Figure 11: Offset Cross Bore for K =3.0.

With the exception of K = 2.25, it was observed that elliptical cross bores gave lower principal stresses than those of circularly shaped ones ranging from offset position 0 to approximately 0.6 for all the studied thickness ratios. Only, in K = 2.25 where the maximum principal stresses predicted by the elliptical cross bores were lower than those of circular cross bores in all the offset positions. This occurrence at K =2.25 signifies the existence of hoop stress transition point, probably from plain stress to plain strain. For the other thickness ratios, the prediction of equal stress magnitudes between the circular and elliptical shapes occurred between 0.6 and 0.8 offset positions. Thereafter, the circular cross bores gave lower stresses.

Generally, the variation in stress between the two shape profiles was more pronounced at the radial position. Table 2 shows a summary of stress variation between the two shapes at radial position, taking elliptical shape as the reference.

Overall, the stress variation at radial position ranged from 44.6% to 66.9% depending on the thickness ratio. The lowest and highest stress difference was noted at K = 1.75 and 3.0, respectively. Nevertheless, the stress variation between the two shapes tended to reduce as the cross bore offset ratio increased.

As illustrated in Figures 5 to 11, the circularly shaped cross bore gave low stresses at the 0.9 offset position except in K = 2.25. However, only a mere 2% reduction in hoop stress would be gained by use of an elliptically shaped cross bore instead of a circular one at 0.9 offset position in K = 2.25, despite the manufacturing difficulties. In general, the magnitude of hoop stress generated due to construction of a cross bore depend on the cross bore diameters ratios and their orientation with the principal axes of the main cylinder, among other factors. With optimal configuration for minimal hoop stresses occurring when the diameter ratio is 2 and the major diameter denoted as "a" is parallel to the direction of hoop stress of the vessel (see figure 1). At radial position, the configuration of the elliptical cross bores satisfies the two optimum conditions leading to generation of lower stresses than circular shaped ones whose diameter ratio is a unit.

In any offset position, the axis of a circular cross bore does not intersect with that of main bore. Thus, when the cross bore is viewed at the intersection between the cross bore and the main bore at any of these offset positions, it resembles a slender hole with a different diameter ratios. The major diameter "a" of this slender hole is parallel to the hoop direction of the cylinder. The major diameter increases with increase in offset location ratio, as the minor diameter "b" reduces. The diameter configuration ratio of $a > b$ gives low hoop stressesas reported by Harvey [16]. This sensation authenticates the low stress observed whenever a circular cross bore is positioned at any offset position.

In contrast, whenever an elliptical cross bore is positioned at an offset position it resembles an ellipse when viewed at the intersection between the main bore and the cross bore. The major diameter "a" is parallel to axial direction and reduces with increase in offset location ratio. Whereas, the minor diameter "b" which is parallel to the direction of hoop stress increases with increase in the offset ratio (see figure 1). The configuration with diameter ratio of $a < b$ gives high stress magnitudes as reported by Harvey [16]. This phenomenon explains the high stress magnitudes experienced in elliptical cross bores when they are placed in an offset position.

As discussed in the preceding paragraphs, the shapes of the two types of cross bores when viewed at the intersection with the main bore, were observed to change in contrariwise manner with increase in the offset location ratio. Therefore, at a particular offset ratio the shapes of the two cross bores would be relatively similar. This occurrence explains the prediction of equal stress magnitudes from both shapes of cross bore when the offset ratio was between 0.6 and 0.8.

Table 2: Comparison between Hoop Stresses due to Radial Circular and Elliptical Shaped Cross Bores

Thickness	Circular Shape	Elliptical Shape	Percentage difference %
1.4	8.212	5.162	59.1
1.5	6.658	4.438	50.02
1.75	4.944	3.419	44.6
2.0	4.64	2.885	60.8
2.25	4.255	2.634	61.5
2.5	3.944	2.393	64.8
3.0	3.743	2.242	66.9

3.2 Hoop Stress Concentration Factor

Since the peak stresses in cross bored thick cylinders do not necessarily occur at the intersection of the main bore and cross bore (nominal area). The stress concentration factor was defined as the ratio of localised critical stresses in a cross bore cylinder to the corresponding similar plain cylinder. This particular definition of SCF exemplifies the stress concentration intensity at each point of concern.

It is important to mention that in most engineering design applications, the strength of a component is based on the peak stresses [11]. Therefore, the SCF for each cylinder was calculated based on locations with the highest magnitudes of hoop stress in the cylinder.

3.3 Effects of Cross Bore Shapes on Hoop Stress Concentration Factor

Figures 12 to 18 show the comparison of stress concentration factors predicted by circular and elliptical cross bores together with a plain cylinder at each offset position for thickness ratios, K = 1.4, 1.5, 1.75, 2.0, 2.25, 2.5 and 3.0.

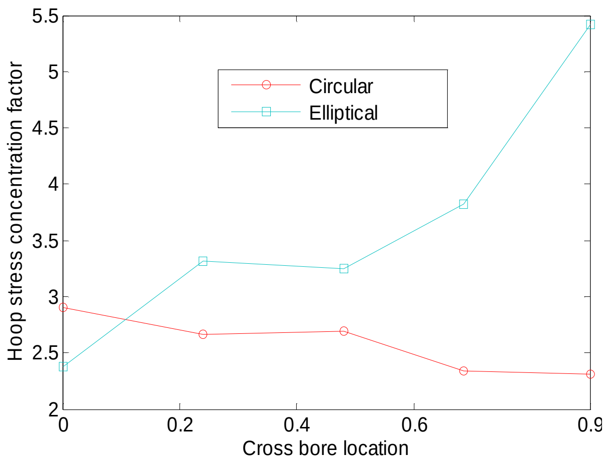

Figure 12: Offset Cross Bore for K=1.4.

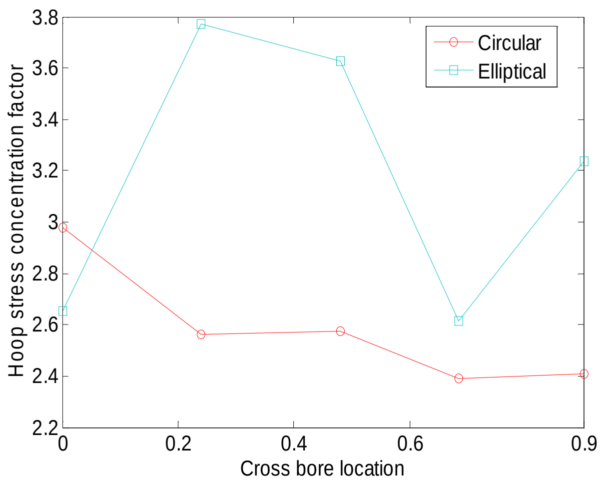

Figure 13: Offset Cross Bore for K=1.5.

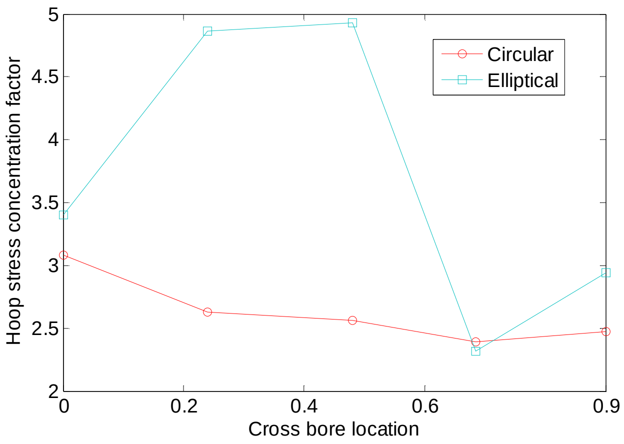

Figure 14: Offset Cross Bore for K=1.75.

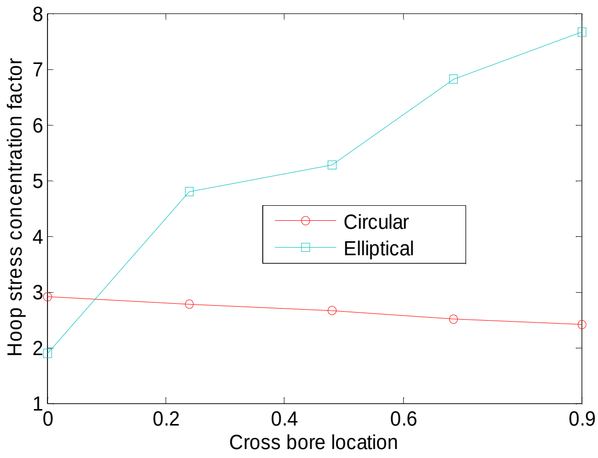

Figure 15: Offset Cross Bore for K=2.0.

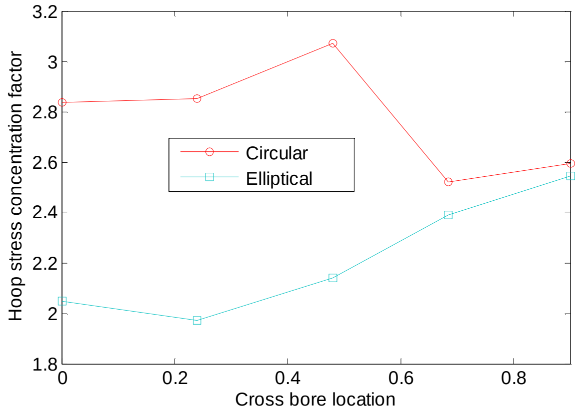

Figure 16: Offset Cross Bore for K=2.25.

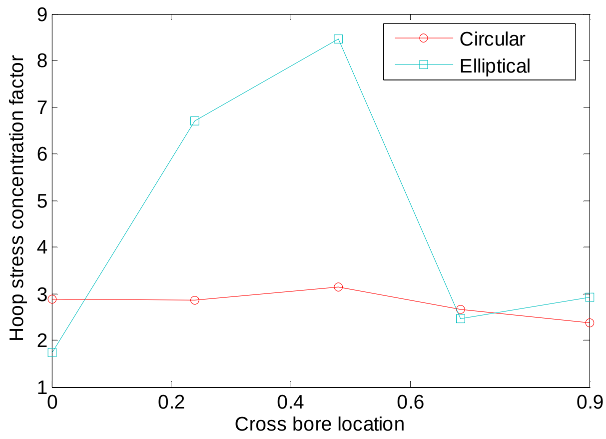

Figure 17: Offset Cross Bore for K=2.5.

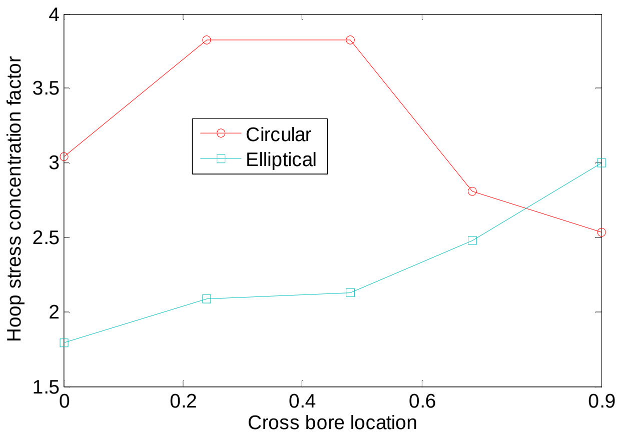

Figure 18: Offset Cross Bore for K=3.0.

With the exclusion of K = 1.75, the SCFs at the radial position due to the elliptically shaped cross bores were lower than that due to circularly shaped ones. This occurrence signified an existence of stress concentration transition point at K = 1.75. The lowest SCF magnitude recorded at this radial position was 1.733 at K = 2.5. Noticeably, this magnitude also doubled as the overall lowest magnitude due to elliptically shaped cross bores. Similar to the preceding sections, offsetting of elliptically shaped cross bores led to the increase of SCF magnitudes. The highest SCF due to elliptically shaped cross bores was recorded at 0.48 offset ratio with a magnitude of 8.457.

On the other hand, the minimum overall SCF magnitude due to a circularly shaped cross bore occurred at 0.9 offset position in K=1.4, with a magnitude of 2.312. In contrast, the highest magnitude occurred at 0.24 at K=3.0 with a magnitude of 3.825. In this regard, therefore, the optimal location of elliptical cross bores reduce SCF magnitudes by 33% in comparison to a similar circular cross bore. However, an incorrect positioning of the same cross bore may lead to a rise of SCF magnitude by 121%.

3.4 Optimization of Cylinder Thickness Ratio and Cross Bore Locations

In the design of pressure vessels, various types of cylinders with varying geometric parameters are considered for different applications. Therefore, the need for identifying an optimal cross bore location for each thickness ratio, taking into account the shape, is important. The graphs showing the comparison between optimal SCF magnitudes predicted by circular and elliptical cross bores at each thickness ratio and offset positions are illustrated in Figures 19 and 20, respectively.

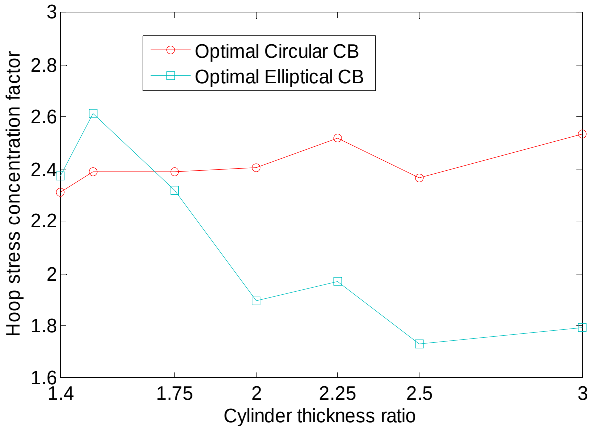

Figure 19: Optimal SCF vs Thickness Ratio

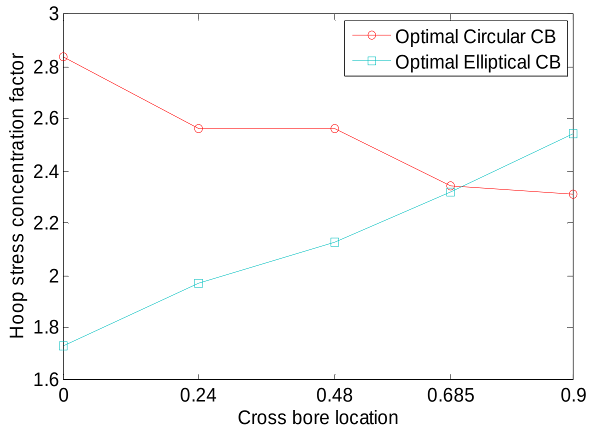

Figure 20: Optimal SCF vs Cross Bore Location

Table 3: Optimum Thickness Ratio

K	1.4	1.5	1.75	2.0	2.25	2.5	3.0
SCF	2.312	2.392	2.319	1.898	2.05	1.733	1.794
Location	0.9	0.685	0.685	0	0	0	0
Shape	Circular	Circular	Elliptical	Elliptical	Elliptical	Elliptical	Elliptical

Table 4: Optimal Offset Locations

Location	0	0.24	0.48	0.685	0.9
SCF	1.733	1.971	2.128	2.319	2.312
K	2.5	2.25	3.0	1.75	1.4
Shape	Elliptical	Elliptical	Elliptical	Elliptical	Circular

Subsequently, the optimal shape and location were selected from these two graphs using the lowest SCFs. The optimum thickness ratio and location are summarised in Tables 3 and 4.

This optimisation process revealed that three of the cylinder sizes, namely K=1.4, 1.75 and 2.5 had the same optimal SCF magnitude. Thus, the same cylinder satisfied optimal design requirements for both the cross bore location and shape. For a circular cross bore, coincidence in SCF between the optimum thickness and location occurred in K=1.4 at the 0.9 offset position which also gave the best circular shape. Whereas for an elliptical shape, similar coincidence in SCF occurred respectively in K=1.75 and 2.5 at 0.685 and 0 offset positions. It is worthwhile noting that elliptical cross bore predicted the overall minimum stress concentration factor, despite being associated with high manufacturing cost or difficulties.

4. CONCLUSIONS

- Elliptical shaped cross bore predicted lower hoop stresses at radial position than circular ones. The variation in hoop stress between the two profiles ranged from 44.6% to 66.9% depending on the thickness ratio.
- With exception of K= 2.25, circular cross bores predicted lower hoop stress at 0.9 offset location ratio than elliptical ones
- The minimum SCF magnitude due to circular cross bore occurred at 0.9 offset position in K = 1.4, with a magnitude of 2.312. On the other hand, the lowest SCF magnitude produced by elliptical cross bore occurred at radial position with magnitude of 1.733 at thickness ratio of 2.5.

- Optimal location of elliptical cross bores reduce SCF magnitudes by 33% in comparison to a similar circular cross bore. However, an incorrect positioning of the same cross bore may lead to a rise of SCF magnitude by 121%.
- For a circular cross bore, coincidence in SCF between the optimum thickness and location occurred in K=1.4 at the 0.9 offset position which also gave the best circular shape. Whereas for an elliptical shape, similar coincidence in SCF occurred respectively in K=1.75 and 2.5 at 0.685 and 0 offset positions, respectively.

LIST OF ABBREVIATIONS

K Thickness ratio (outer diameter to inner diameter)

SCF Stress Concentration Factor

a Radius/ Major radius

b Minor radius

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